Five-year soil moisture response of typical cultivated grasslands in a semi-arid area: Implications for vegetation restoration

Zhi-Qiang Dang[1,§], Ze Huang[1,§], Fu-Ping Tian[2], Yu Liu[1], Manuel López-Vicente[3], Gao-Lin Wu[1,4,*]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Northwest A&F University, Yangling, Shaanxi, China

[2]Lanzhou Institute of Husbandry and Pharmaceutical Sciences of Chinese Academy of Agricultural Sciences, Lanzhou, Gansu 730050 China

[3] Genetics, Genomics and Breeding of Fruits and Grapevine Laboratory, Department of Pomology, Experimental Station of Aula Dei, EEAD-CSIC, Zaragoza 50059, Spain

[4] CAS Center for Excellence in Quaternary Science and Global Change, Xi'an, 710061, China

[§] These authors contributed equally to this work and are co-first authors.

** Corresponding author e-mails: wugaolin@nwsuaf.edu.cn (G.L. Wu)*

***Post address**: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences / Northwest A&F University, NO. 26 Xinong Road, Yangling, Shaanxi Province 712100, Peoples Republic of China.*

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Abstract

Soil water deficit is one of the important abiotic stresses affecting vegetation restoration. The magnitude and spatiotemporal dynamics of soil water content (SWC) provide basic guidance for optimal vegetation restoration. In a semiarid Chinese area, the changes in the soil water storage (SWS) of five cultivated grasslands and one wasteland were observed, to evaluate the water consumption at different soil depths (0–100 cm), from 2008 to 2012. The plants of the three leguminous species consumed more water in deep soil layers (80–100 cm) and produced more aboveground biomass than the plants of the two gramineous species. The gramineous plants mainly consumed shallow soil water (0 ≤ 30 cm). The soil water deficit in the whole soil profile of *Medicago sativa* grassland (43–48%) was significantly higher than the deficit of the gramineous grasslands ($p < .05$). After 5 years of planting, the SWC of *Agropyron cristatum* grassland (21%) was the highest in the 20- to 80-cm soil layer. The variation of SWS in *M. sativa* grassland did not significantly differ during this period, although its mean value was 28% lower than the value in *A. cristatum* grassland

(181 mm). At the end of the experiment, leguminous grasslands caused a serious soil water shortage deficit in the 80- to 100-cm soil layers. These results underscore that vegetation type determines the vertical distribution of soil water deficit, particularly in deep layers. To promote long-term sustainability of water resources, planting *A. cristatum* may be a good choice for early grassland restoration in arid areas.

KEY WORDS: *arid area, grassland restoration, soil water content, soil water deficit degree*

1. INTRODUCTION

Vegetation restoration is one of the most important and effective way to reduce soil and water loss (Yu et al., 2015). The restoration of natural grasslands and the establishment of artificial grasslands are common practices in the arid areas of the world. In these landscapes, and during the process of restoration, the soil water content (SWC) is the key limiting factor for vegetation growth (Siltecho et al., 2015; Wang, Li, Xiao, Berndtsson, & Pan, 2007; Wang, Fan, Cao, & Liang, 2016). Soil water is not only the basis for plant survival in terrestrial ecosystem, but also the most active part within the watershed water cycle because it affects plant growth, ecological environment construction and the rational distribution and efficient utilization of water resources. In semi-arid regions, the current global warming is aggravating drought conditions by increasing the potential evapotranspiration (Muluneh, Biazin, Stroosnijder, Bewket, & Keesstra, 2015).

Previous studies have indicated that the different species cultivated in grasslands play an important role in the observed values of the soil hydraulic parameters (Mao and Cherkauer, 2009; Gonzalez-Sosa et al., 2010). Different cultivated grasslands have critical influence on soil water variation (Huang et al., 2018). In arid regions, grassland sustainability is commonly associated with the soil water availability (Liu, Chen, & Xu, 2010; Rodriguez-Iturbe, 2000). Leguminous plants can be used to increase grassland above-ground biomass (Wu, Liu, Tian, & Shi, 2017) and community diversity (Daniel, Robert, & Roch, 1999), as well as to improve soil structure (Lal, 1996). However, the high water consumption of leguminous species has become the main limiting factor for their popularization in arid areas. In particular, the soil in *Medicago sativa* grasslands can be severely, even extremely, desiccated over planting time (Cui et al., 2018). On the other hand, the different grassland species have distinct canopy structure, soil cover rates and root distribution that may result in the modification of the soil properties and thus affecting soil water infiltration (Angers and Caron, 1998; Bormann and Klaassen, 2008; Vervoort, Dabney, & Römkens, 2001; Wang, Li, Xiao, Berndtsson, & Pan, 2007; Yu et al., 2015; Zhao, Wu, Zhao, & Feng, 2013). Fan et al. (2010) observed that the root biomass in the 0-10 cm soil layer accounted for 65.9%-82.6% of the total biomass in the 0-40 cm soil layer and the characteristics of the root distribution had certain feedback on the soil physicochemical properties.

The maintenance of a certain level of above-ground biomass is essential for improving ecological indicators in restored landscapes. At the same time, higher biomass implies a higher consumption of soil water. Thus, trade-off the relationship between biomass and soil water content is necessary to achieve a sustainable vegetation restoration. The main objectives of this study were to characterize and evaluate the variation of the above-ground biomass and soil water content in different grasslands under semi-arid conditions. The relationships between them were explored to choose the most suitable species for the sustainable development of grassland restoration. We explored the relationships between the above-ground biomass and the soil water storage deficit with the increase of planting years. First, we determined the time series changes of SWC in five different grasslands along the soil profile (0-100 cm depth) and the above-ground biomass during a five-year period, from 2008 to 2012. Then, the relationships between the above-ground biomass and the soil water storage deficit were analyzed with the increase of the planting age. Finally, these results were compared with the observed dynamics in a wasteland that acted as control area. The findings and conclusions of this study can provide an evidence for selecting proper grass species to build artificial grassland in semi-arid regions.

2. MATERIALS AND METHODS

2.1. Study sites

This study was conducted in the Regional Experimental Station of Lanzhou Institute of Animal Husbandry and Veterinary Medicine, Chinese Academy of Agricultural Sciences, which is located in Lanzhou city, Gansu Province, China (36°01’N, 103°45’W). This area belongs to the semi-arid and gully canal hilly area within the western Loess Plateau. The main soil type is calcareous loess and the soil water content at field capacity is about 19.3% volume. The soil parent material is quaternary aeolian loess, which is characteristic of the Chinese loess region (Li, Zhao, Song, & Zhu, 2010). The average altitude of the test site is 1,732 m a.s.l. In this area, the native grassland ecosystem is mainly dominated by *Stipa capillata*. During the growing season of the test period (2008-2012), from April to September, the mean maximum and minimum temperature was 23.1°C and 9.8°C, respectively; and the mean annual precipitation was 324.5 mm, most of them recorded between July and September. The average annual evaporation is about 1450.0 mm and the sunshine duration is 2651.4 h.

2.2. Experimental design

The experimental site was planted with sorghum (*Sorghum bicolor* L.) continuously from 1970 to 2005 and was abandoned from 2005 to 2007 (grazing was excluded). Then, we selected five cultivated grasslands and one abandoned cropland (natural successional species were present, e.g., *Chenopodium album* L. and *Agropyron cristatum* L.) where we established the study site. Five main forage grasses, widely grown across arid areas, were selected and cultivated, including three leguminous species (*Medicago sativa* L., so-called "A"; *Onobrychis viciifolia* Scop, so-called "B"; and *Coronilla varia* L., so-called "C") and two gramineous species (*Poa pratensis* L., so-called "D"; and

Agropyron cristatum L. Gaertn., so-called "E"). Besides, one abandoned cropland (so-called "F") was added as control plot. According to the different sowing rates of the various herbage, the five grasslands were planted in early April 2007. We designed the experiment following a randomized plot design. Three experimental plots (10 m × 20 m) were established randomly within each grassland area. During the planting, the criteria for seed density followed the local farmers experience for many years. All plots were weeded manually to remove unplanted species and no irrigation was applied from 2008 to 2012. These plots were not fertilized during planting. The five annual surveys to measure the SWC and aboveground biomass were conducted in the same month, in August, in order to obtain comparable data.

2.3. Soil sampling and measurements

The roots of the grass are mainly distributed in the 0–100 cm soil layers. Thus, the SWC in the 0-100 cm soil layers were measured. Soil samples were collected every 10 cm intervals up to a maximum depth of 100 cm by using a 4-cm diameter soil auger. In each plot, three samples were randomly collected and three soil cores were randomly taken with a stainless cylinder for assays of soil water. A total of 900 soil samples were taken and carried into the laboratory. All soil samples were weighed immediately after their collection, then dried at 105°C for 24 h, and finally weighed again. A 5-cm diameter and 5-cm high stainless-steel cutting ring (ca. 100 cm^3) was used to estimate the soil bulk density (BD) at adjacent points to the soil sampling points. The BD was also measured every 10 cm intervals up to a maximum depth of 100 cm and then averaged to obtain the mean value of the soil profile.

2.4. AGB estimation

Five quadrats of 1.0 m^2 (1.0 m × 1.0 m) were randomly set up in each plot in late August every year (2008–2012). The above-ground biomass (AGB) was estimated after cutting the plant stems at the soil surface level and then sealed in labeled sealing bags. Each sample was weighed while the plant material was fresh and then re-weighed after drying at 65°C to a constant weight.

2.5. Assessment of SWS and deficit

The BD was calculated based on the oven-dried weight of the composite soil samples (Deng et al., 2013). The soil water storage (SWS) was calculated for all samples collected at each grassland site using the approach of Gao et al. (2014):

$$SWS = h \cdot \rho \cdot \vartheta \cdot 10^{-1} \quad (1)$$

where h is the soil depth (cm), ρ is the soil bulk density (g cm^{-3}), and ϑ is the gravimetric soil water content (% weight).

The soil water storage deficit degree (SWSD) was calculated as follows (Wang, Huang, & Lou, 2004):

$$SWSD = Da / Fc \times 100\% \quad (2)$$

$$Da = Fc - W \quad (3)$$

where *Da* is the soil water storage deficit (mm), and *Fc* is the soil water content at field capacity (mm). The *Fc* was determined by means of the ring knife method.

2.6. Statistical analyses

Two-way analysis of variance (ANOVA) was used to assess the effects of planting years, grass species and their interactions on the soil water storage and above-ground biomass. Significant differences were evaluated by using Tukey's honestly significant difference (HSD) test at the 0.05 level. All data analysis was done by using SPSS 18.0 software (SPSS, 2009). Regression lines were plotted to express the relationships between the soil water storage (0-100 cm) and above-ground biomass. Data in the results were expressed as mean values ± standard deviation (M ± SD). The figures were plotted by using Origin Pro 9.1 software.

3. RESULTS

3.1. Variations of SWC after five planting years

The SWC in the five artificial grasslands and the abandoned cropland clearly varied between them and along the different soil depths (Fig. 1). The lowest SWC was found in the soil layers at 0 and 30 cm soil depth in the *O. viciifolia* grassland. In the whole analyzed soil profile (0-100 cm), the SWC of the three leguminous grasslands was lower than that of the gramineous grasslands. In particular, in the *M. sativa* grassland the SWC was always very low and the observed high-water consumption of the deep soil water could possibly trigger soil desiccation. Along the soil profile, in the range of 0-100 cm, the water deficit of alfalfa grassland was the largest and this deficit decreased with increasing the soil depth. Conversely, the SWC was relatively high in the *P. pratensis* and *A. cristatum* grasslands. Related to the planting years, the SWC of the two gramineous grasslands increased with increasing the age.

3.2. Annual variations of SWS and AGB

The statistical analysis showed that the grassland type had significant effects on the SWS and ABG ($P < 0.01$), while the effects of planting year was not significant ($P > 0.05$, Table 1). The grassland type and year interaction was significant in the SWS and ABG ($P < 0.01$). The SWS of the leguminous grasslands at 0-100 cm soil layers was lower than that of the gramineous grasslands (Fig. 2). During the 5-year test period, the lowest value of the SWS was observed in the *O. viciifolia* grassland (138.51

± 0.99 mm) in 2009 ($p < 0.05$), and the highest SWS value appeared in the *A. cristatum* grassland (185.45 ± 1.90 mm) in 2010 ($p < 0.05$). However, the SWS had no significant difference during the five years in the *M. sativa* grassland and its average value was about 28% lower than the average SWS in the *A. cristatum* grassland.

On average, the AGB of the *M. sativa* grassland (27,438.73 ± 12,704.94 kg hm^{-2}) was higher than the AGB in the other grasslands (Fig. 3). The abandoned cropland presented the lowest average AGB value (5,206.41 ± 1,722.37 kg hm^{-2}). From the total measurements, the highest AGB appeared in the *M. sativa* grassland (42,225 ± 888.53 kg hm^{-2}) in 2012, and this values was significantly different from the AGB of the other grasslands ($p < 0.05$). After the five planting years, the average AGB of the leguminous grasslands was much higher than the AGB of the gramineous grasslands, although their average soil water storage (SWS) was lower (Fig. 4). The maximum average SWS was observed in the *A. cristatum* grassland (179.31 ± 6.02 mm), and this difference was statistically significant with regard to the other grasslands ($p < 0.05$).

3.3. Relationships between the AGB and SWSD

The evolution of the AGB described a parabolic curve, whereas the evolution of the soil water storage deficit (SWSD) showed a continuous downward trend over the planting time (Fig. 5). The AGB curve of the *M. sativa* grassland described a continuous rise and the degree of its SWSD was very large (>43%, R^2 = 0.79). On the other side, the SWSD was minimum (<32%, R^2 = 0.74) in the *A. cristatum* grassland. In all grasslands, the highest levels of the SWSD were obtained at the third year after sowing. During the test-period, the AGB was firstly reduced and then increased in the abandoned cropland and the maximum value appeared in the fourth year after sowing.

4. DISCUSSION

In the present study, we explored the relationship between the above-ground biomass and soil water storage deficit in five different cultivated grasslands and one abandoned cropland. Water is one of the important components of plants. The survival, growth, development and reproduction of plants cannot be separated from water. In semi-arid areas, with low rainfall and high evaporation, soil water is an important way of water absorption in plants. In this experiment, strong water consumption caused the highest SWSD on the *M. sativa* grassland. This species has a strong root system, which can use shallow and deep soil moisture, and then, affected the redistribution of soil water content and soil moisture. Plants with large leaf area, high yield and deep roots consume more soil water (Cheng, Huang, Shao, & Warrington, 2009). With the growth of *M. sativa* the water demand increased and the soil moisture of shallow and deep layers decreased. It is known that *M. sativa* is a kind of plant with high water consumption requirements and it can even absorb water from deep soil layers by using its extensive root system (Cui et al., 2018). Previous studies have found that, with increasing the age of alfalfa grassland, the main soil depth where water consumption was predominant was gradually deepening (Ren, Li, Wang, & Fang, 2011). On the other hand, *A. cristatum* and abandoned cropland only consumed shallow soil water and this fact was related to the biological characteristics of the vegetation. *A. cristatum* and the grass on the abandoned cropland have an elongated blade and a thicker stratum corneum, which reduced the amount of transpiration. *A. cristatum* has formed a series of physiological and ecological mechanisms to resist drought stress because it has survived in dry environments for a long time. Under natural conditions, Singh, Milchunas, et al. (1998) observed that the change of water content in deeper soil layers was smaller than in topsoil and can be used as a potential resource, which can buffer the influence of precipitation and keep the vegetation stability of the grass community. The average SWC value in the leguminous grasslands was lower than that in the gramineous grasslands. The utilization of shallow water was particularly prominent in *M. sativa* grassland. Many studies have shown that leguminous plants consume more water than gramineous plants in arid and semi-arid areas (Cui et al., 2018; Huang et al., 2018). Other studies have indicated that the roots of the leguminous plants (*C. korshinskii* and *M. sativa*) were deeply distributed and could consume more deep soil water (Huang et al., 2017; Jia and Shao, 2013). Previous studies showed that the differences of SWC among different soil profiles and grasslands were mainly affected by the root distribution and depth (Cheng, Huang, Shao, & Warrington, 2009; Schenk and Jackson, 2002; Yang, Wei, Chen, Chen, & Wang, 2014). Deep-root plants are high water-consumption plants that can use deep soil water, while plants with fiber roots are relatively low-water consumption plants (Jia and Shao, 2013; Pelaez, Distel, Boo, Elia, & Mayor, 1994; Zhao, Jia, Zhu, & Shao, 2017). Therefore, a large amount of deep soil water was used in the *M. sativa* grassland and a small amount of deep soil water was used in the *A. cristatum* grassland and abandoned cropland.

The lack of soil moisture affects dry matter yield of grassland and this may be related to the growth of cultivated species, root characteristics and transpiration. The soil water deficit did not always reduced the dry matter yield and a large amount of soil water was consumed and converted into dry matter yield in the *M. sativa* grassland. The gramineous grassland had a low dry matter weight. The statistical test showed that the grassland type had significant effects on the ABG ($P < 0.01$), while the effects of planting year were not significant ($P > 0.05$). The evolution of the AGB described a parabolic curve, whereas the evolution of the soil water storage deficit (SWSD) showed a continuous downward trend over the planting time. With the change of planting year, the AGB was also changing. The effect of soil water shortage on grassland biomass was more obvious. On the other hand, it was indicated that the variety of plants was different to the degree of water utilization. Some of the results were similar to those of previous studies. Grasslands with gramineous plants have fiber roots in deep soil layers and the distribution of underground biomass is limited, thus reducing the consumption of soil water (Ruiz-Sinoga et al., 2011). In arid areas, grasslands with leguminous plants have deep main roots that need more water during the growing season, which tend to dry the whole soil profile and reduce the water supply (Xu, Gichuki, Shan, & Li, 2006). In this study, field observations showed that the time stability of SWC increased with increasing the soil depth. This finding was consistent with the results of Fu, Wang, et al. (2003) and Liu and Shao (2014), who found that the SWC of deeper soil layers was relatively stable despite the seasonal variation.

The soil water storage is an important index of water resources and the basis of vegetation planting, especially in arid areas (Zhao, Jia, Zhu, & Shao, 2017). The SWS in the *M. sativa* grassland did not significantly vary during the five-year test period, although it was about 28% lower than the SWS in the *A. cristatum* grassland (181 mm). Soil water is consumed by evaporation and transpiration. The distribution model of soil water is related to the AGB, root biomass and plant species distribution. High yield requires more water and the presence of deep roots that absorb deeper soil water; and the different plant species have different transpiration rates (Siltecho et al., 2015; Wang, Li, Xiao, Berndtsson, & Pan, 2007; Wang, Fan, Cao, & Liang, 2016). Previous studies have suggested that the root system of the leguminous grasslands was deeper, which resulted in a higher consumption of soil water than the consumption of the gramineous grasslands (Huang et al., 2018). This process could further aggravate the soil water deficit and hinder the sustainability of field grasslands. Although the AGB of the leguminous grasslands was the highest in this study, more specific studies are still needed to determine the potential mechanism of water consumption in each plant. Therefore, in order to give full play to the characteristics of species, it is necessary to deeply study its ecological effects in future.

5. CONCLUSIONS

The AGB and soil water response (content and storage deficit) of five different cultivated grasslands were compared and analyzed by long-term field measurements obtaining significant differences among them. The vegetation type clearly determined the predominant depth of the soil water deficit and its vertical distribution under semiarid conditions. The AGB in the leguminous grasslands (*M. sativa* L., *O. viciifolia* Scop, and *C. varia* L.) was higher than in the gramineous grasslands (*P. pratensis* L., and *A. cristatum* L. Gaertn.). A large amount of soil water was consumed by the *M. sativa* plants, whereas the largest SWS appeared in the *A. cristatum* grassland. Compared with the other grasslands, the best soil water status was observed in the *A. cristatum* grassland. Therefore, planting *A. cristatum* as a pioneer grass species appears as a good choice for long-term vegetation restoration in semiarid areas.

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ORCID

Yu Liu: https://orcid.org/0000-0003-0706-4026

Manuel López-Vicente: https://orcid.org/0000-0002-6379-8844

Gao-Lin Wu: https://orcid.org/0000-0002-5449-7134

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FIGURE 1. Time series changes of soil water content (SWC) in the different grassland types in 0- to 100-cm soil depth at 10-cm intervals, from 2008 to 2012. The grassland types are (a) (*Medicago sativa*), (b) (*Onobrychis viciifolia*), (c) (*Coronilla varia*), (d) (*Poa pratensis*), (e) (*Agropyron cristatum*), and (f) (abandoned cropland).

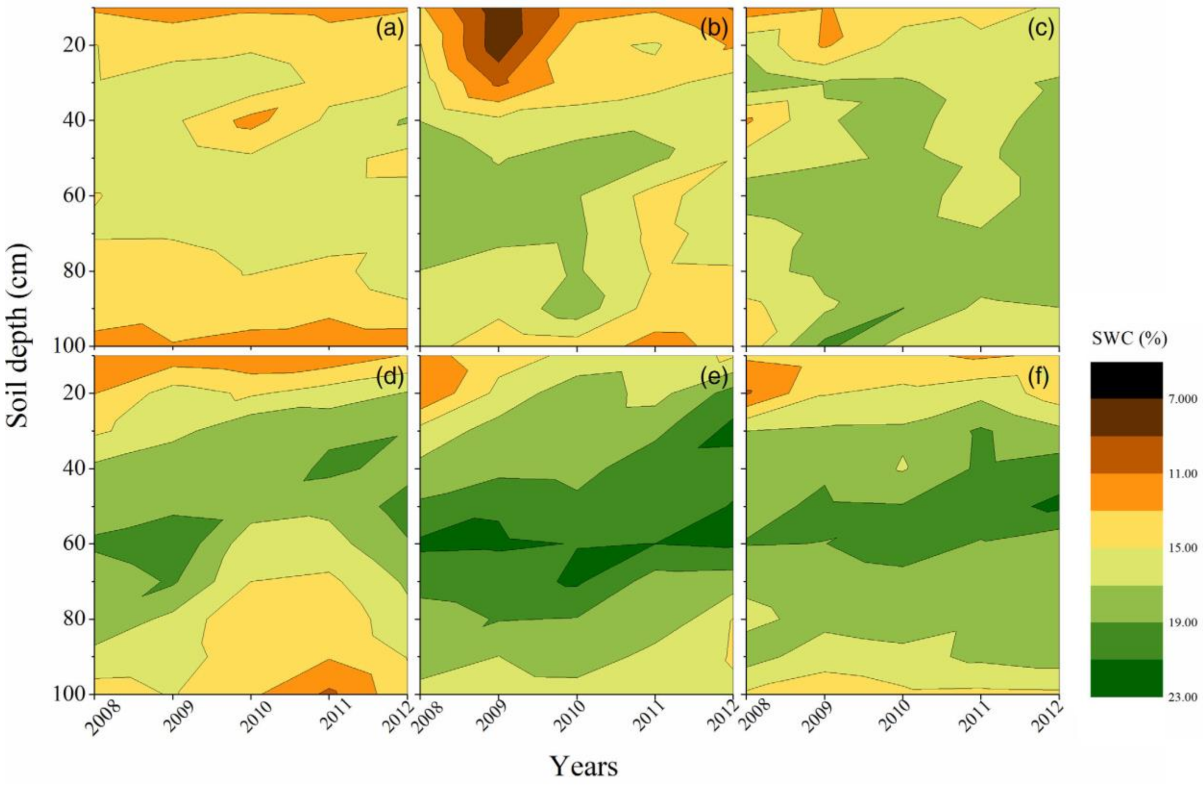

FIGURE 2. Soil water storage (SWS) variation on 0- to 100-cm soil layers in the different grassland types from 2008 to 2012 (M ± SD). The proportion of the SWS in the different years is labeled with different colors. Different lowercase letters above them indicate significant differences among the means at p < .05 in the same year. Different capital letters indicate significant differences among the SWS in the different years of the same grassland type at p < .05.

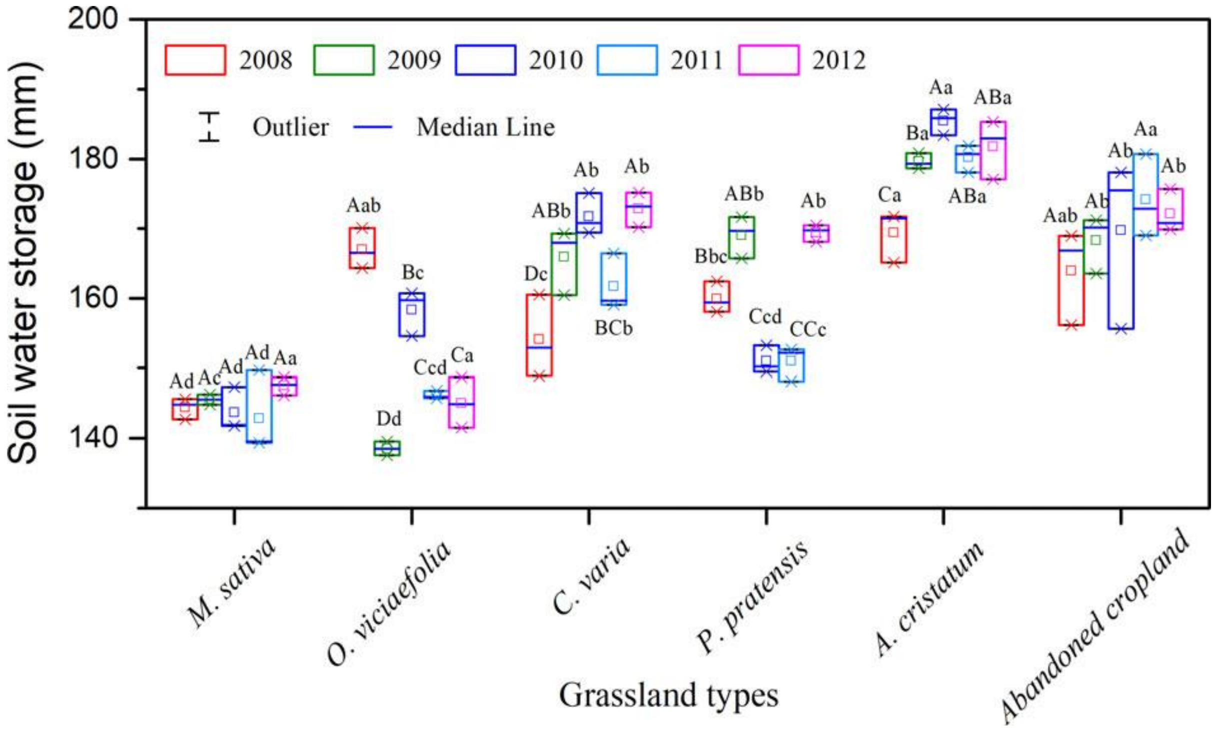

FIGURE 3. Changes of the aboveground biomass (AGB) in the different grassland types from 2008 to 2012 (M ± SD). The proportion of the AGB in the different years is labeled with different colours. Different lowercase letters above them indicate significant differences between the means at p ≤ .05 in the same year. Different capital letters indicate significant differences between the AGB in different years of the same grassland type at p ≤ .05.

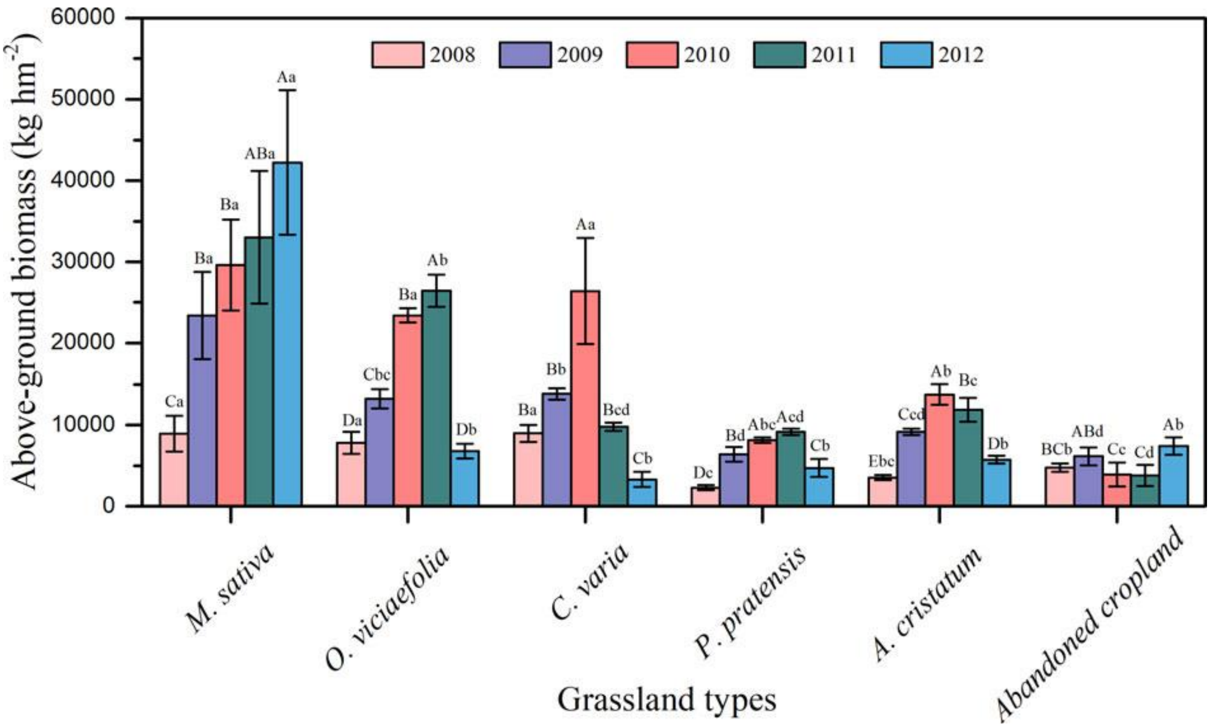

FIGURE 4. Changes of the average aboveground biomass (a) and soil water storage (b) in the different grassland types from 2008 to 2012 (M ± SD). Different lowercase letters above them indicate significant differences between the means at p ≤ .05 in the different grassland types.

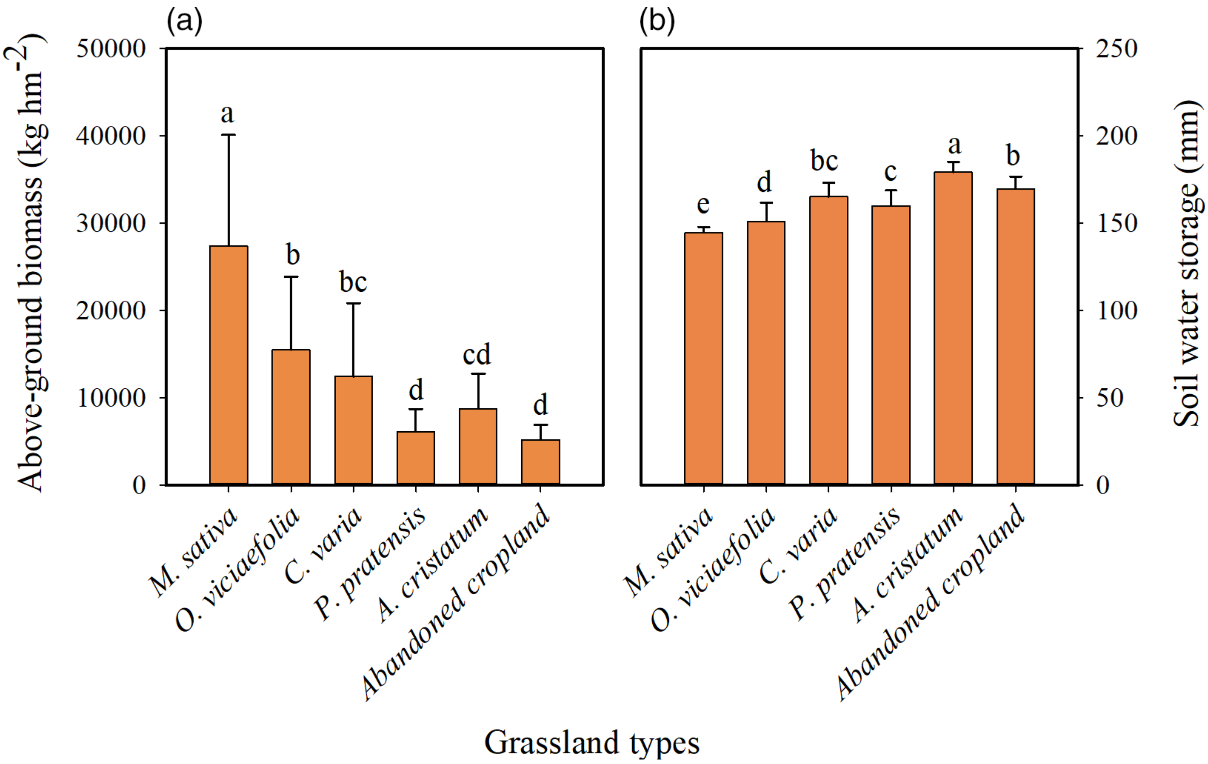

FIGURE 5. Relationship between the aboveground biomass (AGB) and soil water storage deficit (SWSD) degree (the total of 0- to 100-cm soil layers) with the increase of planting years. Yellow line represents SWSD, and blue line represents AGB. The grassland types are A (*Medicago sativa*), B (*Onobrychis viciifolia*), C (*Coronilla varia*), D (*Poa pratensis*), E (*Agropyron cristatum*), and F (abandoned cropland).

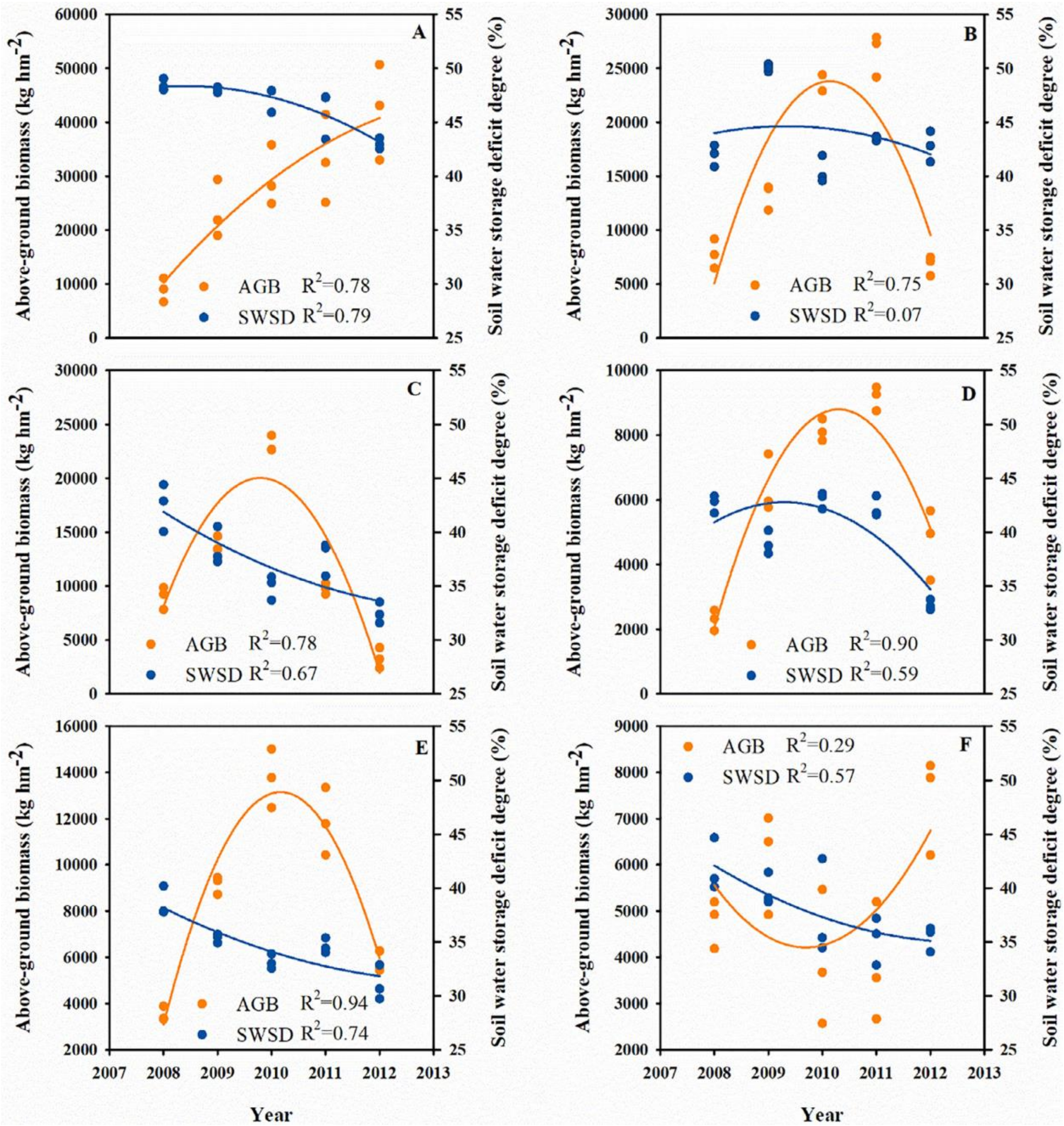

TABLE 1. Results from two-way analysis of variance, testing the effects of planting years, grassland types, and their interaction on soil water storage (SWS) and aboveground biomass (AGB).

Error sources	**Num DF**	***F*-value**	***P*-value**	***F*-value**	***P*-value**
		SWS		AGB	
Grassland types	5	13.352	＜0.001	8.235	＜0.001
Year	4	0.547	＞0.05	2.639	＞0.05
Grassland types × Year	20	10.634	＜0.001	15.779	＜0.001